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HETEROGENEITY IN INNOVATION STRATEGIES, EVOLVING CONSUMER PREFERENCES AND MARKET STRUCTURE[1]:

AN EVOLUTIONARY MULTI-AGENT BASED MODELLING APPROACH

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Abstract

The aims of this paper are twofold. The first is to analyse the interaction between research and development (R&D) activities of firms and heterogeneous consumer preferences in structuring the evolution of an industry. The second is to explore the heterogeneity in firms' innovation strategies. Is heterogeneity sustainable in the long-term and what happens to the market shares of firms having different innovation strategies when a structural market characteristic (market size) or a behavioural rule (R&D intensity) is changed? To answer these research questions, an evolutionary, multi-agent based, sector-level innovation model is designed. The model addresses supply and demand sides of the market simultaneously with the co-evolution of heterogeneous consumer preferences, heterogeneous firm knowledge bases, and technology levels at the micro level.

Keywords: Heterogeneity; innovation strategies; evolutionary economics; agent-based modelling
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1. Introduction

The structure of industrial R&D has undergone considerable change since 1985, particularly in the USA (Mowery, 2009). This change is mostly related to the increase in the number of and heterogeneity among the agents involved and the complexity of the interrelationships. It had everlasting effects on the innovation process. Innovation is a multifaceted phenomenon at the intersection of economics and technology. However, the economics discipline frequently falls short of developing a holistic approach embracing this multi-dimensional phenomenon. Economists develop theories and models to explain social processes, but when the object of analysis is innovation, the intrinsic gap between reality and the representation of reality by scientific endeavour is generally wider than that can be legitimized by its very nature. The size of this gap is even more pronounced when one considers the ever increasing roles innovation plays in the social matrix. Any modelling exercise should address aforementioned heterogeneity among the agents involved and the complexity of their interrelationships. Therein, it is completely plausible that economists should put maximum effort into discovering analytical methods and modelling techniques exploring the mechanisms at work and testing their models against real life data.

For this purpose, following the footprints of eminent work by Nelson and Winter (1982), the Schumpeterian research tradition has been merged with organizational and behavioural elements (especially Cyert and March, 1963; Simon, 1955) within an evolutionary framework of variation, selection and historical time, in order to capture the dynamics of innovation and their impact on growth, trade and technological change (e.g. Dosi *et al.*, 1988) (Gilbert *et al.*, 2001). This research tradition can be regarded as a radical step forward in understanding innovation in a number of ways. First, market competition through technological change, hence innovation, is at the core of neo Schumpeterian and evolutionary economics analysis (Nelson and Winter, 1982). Second, incorporating behavioural and organizational elements enables a more realistic representation of innovation. Last but not the least, this line of research is well equipped with the required modelling techniques to deal with the heterogeneity among the agents involved and the complex interactions between these agents.

This study is designed as an evolutionary, multi-agent based, sector-level innovation modelling exercise. First, this model will be used to analyse the interaction between R&D activities of firms and differentiated consumer preferences in structuring the evolution of an industry. Then, we will explore the heterogeneity in firms' innovation strategies: how the market shares of firms having different innovation strategies are affected by a change in a structural market characteristic**;** market size or a behavioural rule; R&D intensity. The model addresses the supply and demand side of the market simultaneously with the co-evolution of heterogeneous consumer preferences, heterogeneous firm knowledge bases and technology levels at the micro level. In line with the evolutionary modelling tradition, we have a search algorithm (innovation and imitation of products by firms), a selection algorithm (revealed preferences of the consumers), and a population of objects in which variation is expressed and on which selection operates: namely, firms (Windrum, 2004). Firms compete on quality and price of their products in an oligopolistic market whereas consumers, constrained by their computational limits, act to maximize their utility with their product choices. There is continuous firm entry and exit depending on the competitive performance of the firms.

Agent-based modelling (ABM) is the most frequently utilized technique in evolutionary settings (Grebel and Pyka, 2003). In case of innovation at industry level, we are exploring a highly decentralized dynamic search process under strong substantive and procedural uncertainty, where numerous heterogeneous agents search in parallel for new products/processes, but are interlinked through market and non-market interactions (Dawid, 2006). Several evolutionary modelling exercises in the literature repeatedly showed that ABM is capable of simulating such a platform where these peculiarities are successfully mapped into model designs. Furthermore, ABM is offering a platform for inter and trans-disciplinary research, which is again congruent with the requirements of innovation studies. With agent-based modelling, we hope to stretch the trade-off between simplicity in modelling and the complexity of the socio-economic reality.

The paper contributes to evolutionary modelling tradition in a few dimensions. To begin with, it includes an explicit modelling of specific innovation modes. There are three strategy pairs which makes a total of eight exclusive strategies: innovation vs. imitation, technology-push vs. demand-pull, and focused vs. diversified. These innovation modes are selected because they are frequently adopted strategy sets by real firms. Secondly, whereas most evolutionary models focus on process innovation, this one exclusively models product innovation, i.e. technical progress is embodied in products. Firms compete both in the R&D process and goods market rather than in any one of them. Lastly, rather than single-product firms, the market is populated with multi-product firms which can serve to different niches of consumers concurrently. With the continuous introduction of new innovations, products transform from undiscovered to discovered and then from cutting edge product to obsolete. As the product space steadily shifts, the consumers are compelled to redefine their product choices within the given product range.

The rest of the paper is organized as follows: Section 2 is a literature review on product innovation and competition in product markets, and heterogeneity in firms' innovation strategies. The first part of the review presents some empirical findings on the existence of and reasons for heterogeneity in innovation modes from several studies. The second part is on how theoretical models conceptualize product innovation and competition. Section 3 details the simulation model. In section 4, the results of the simulation analyses are discussed. Section 5 concludes.

2. Literature Review

2.1. Heterogeneity in Innovation Modes

From the perspective of evolutionary theory, firm diversity is an essential aspect of the processes that create economic progress (Nelson, 1991). Firms differ in many respects, unavoidably including their innovation patterns. Helfat (1994a, b) for example drawing upon the evolutionary theory argued that tacitness of knowledge and cumulativeness of learning lead to highly firm-specific R&D applications. In the economics of innovation literature, this heterogeneity is either explained by the sectoral (e.g. Pavitt, 1984; Malerba and Orsenigo, 1996; and Dosi *et al*., 1995) or national (e.g. Lundvall, 1992; Nelson, 1993) differences (Srholec and Verspagen, 2008).

The question of heterogeneity in firm innovation strategies is extremely relevant both from a theoretical and practical point of view. At the theoretical level, it is one of the subjects of discussion between the evolutionary and mainstream traditions. From the evolutionary point of view, it provides an insight into the selection mechanism in different market environments. Evolutionary economists predict that selection process picks the firms adopting the strategy that fits best with the environmental conditions. In a similar vein, neoclassical economists assume that agents are perfectly rational and make the best possible choice for themselves or only the firms following the best strategy survive in a competitive environment which corresponds to perfectly rational agents operationalizing the “as if” argument (Friedman, 1953). Hence, the question of heterogeneity in firm innovation strategies addresses the question whether or not the mainstream prediction of homogenous behaviour is observationally equivalent with the outcome of the selection process. From the practical point of view, heterogeneity in innovation provides insights with regard to whether a generic technology policy is likely to be effective (Srholec and Verspagen, 2008).

In an empirical study by Leiponen and Drejer (2007) analyzing the patterns of innovation within and across industries using firm-level survey data from Finland and Denmark, firms within most industries are found to follow multiple patterns of innovation behaviour. Even at very detailed levels of industry classification (four- and five-digit NACE industries) and including all industries for which six or more observations are available, only about half of the observed industries have a dominant innovation regime, defined as 50 per cent or more of the firms in an industry being affiliated with the same regime. The authors interpret this as strategic differentiation or local search activities overcome pressures in the technological environment towards homogenous behaviour, at least in the short term. The multiple patterns of behaviour with regard to innovation may be related to intra-industry differentiation: initial strengths and weaknesses of firms, time of entry into the business, and historical accidents.

Arundel *et al*. (2007) explores the link between the organizational forms and innovation modes (how firms innovate) by developing national aggregate indicators for the EU member states. The innovation mode indicators are calculated using the results of the third Community

Innovation Survey (CIS) for innovation activities between 1998 and 2000 to develop a typology of innovation at the firm level and to calculate the distribution of these innovation types within each of 14 EU countries for which data are available. The paper draws on a taxonomy developed by Arundel and Hollanders (2005), in collaboration with Paul Crowley of Eurostat, in order to classify all innovative CIS respondent firms into three mutually exclusive innovation modes that capture different methods of innovating (lead innovators, technology modifiers and technology adopters), plus a fourth group for non-innovators. The classification method uses two main criteria: the level of novelty of the firm's innovations, and the creative effort that the firm expends on in-house innovative activities.

By applying cluster analysis to a large set of innovation indicators based upon Swiss Innovation Survey 1999 (which, to some extent, also capture non-technological aspects of innovation), Hollenstein (2003) identified five specific innovation modes: science-based high-tech firms with full network integration, IT-oriented network-integrated developers, market-oriented incremental innovators with weak external links, cost-oriented process innovators with strong external links along the value chain and low-profile innovators with hardly any external links. These modes are characterized by the use of several groups of variables: (a) innovation indicators, (b) demand- and supply-side determinants of innovative activity, (c) the firms' position in knowledge networks, (d) several structural characteristics of firms, and (e) measures of firm performance. This study found firstly, that the firms in most innovation modes are distributed across several industries; however, taking the service sector average as the benchmark, three of five innovation modes are (heavily) concentrated in specific industries. Secondly, economic performance is related to the affiliation with a specific innovation mode in only one or two of the five modes, depending on the performance measure used. These results imply that neither the "classical" ranking of industries according to innovativeness nor the classification of firms into unordered categories representing innovation modes of equal "economic value" capture the whole reality.

Srholec and Verspagen (2008) use exploratory factor analysis on micro data from the 3rd CIS in 13 countries to interrogate the claim that national and sectoral differences account for much of the heterogeneity in innovation strategies. The study identifies four ingredients of an innovation (research, user, external and production), and five distinct innovation strategies (high profile, user-driven, externally-sourced, opportunistic, low profile). The analysis concludes that there is a considerable diversity in how firms innovate, and these differences remain very substantial once effects due to different sectoral and national contexts are cancelled out. Variance decomposition analysis revealed that firm-level heterogeneity is the dominating tendency in the data.

2.2. Product Innovation and Competition

Today a big part of the innovative effort is directed towards product innovation and generating a continuous stream of product innovations gives firms a competitive edge in many industries. Besides, process innovation also often originates by a stream of (product) innovations in capital goods and this motivates us even more to explore the economic effects of innovations embodied within products (Marengo and Valente, 2010).

Again in many industries this continuous stream of product innovation goes in parallel with product diversification. Rather than competing on homogeneous products, firms use innovation to bring to the market ever new varieties of products and this creates new market niches. Product differentiation on the supply side is the counterpart of the differentiation of demand. Buyers have heterogeneous needs and preferences and markets are segmented. Thus product innovation is constantly creating sub-markets (Klepper and Thompson, 2006), i.e. transforming industries into systems of weakly competing heterogeneous market segments, with new segments appearing all the time and attracting new potential buyers, and old segments disappearing (Marengo and Valente, 2010).

Economists have developed models explaining creative destruction outlined by Schumpeter. A model of endogenous growth through product innovation by Romer (1990) explicitly incorporates the number of product designs. These new designs (i.e. horizontal innovations) are never close substitutes for existing goods and this precludes Schumpeterian destruction. Five studies that have built on Romer's work, adding product obsolescence, are Segestrom *et al.* (1990), Segestrom (1991), Aghion and Howitt (1992), and Grossman and Helpman (1991a, 1991b). These papers advance models in which firms compete against one another through vertical product innovations. Grossman and Helpman coin the phrase "quality ladder" to describe the stages in a product's life: undiscovered to discovered cutting edge product to obsolete due to newly discovered products. In adding obsolescence to Romer's framework, these models have abandoned horizontal innovation altogether, although Grossman and Helpman (1991b) show that their vertical innovation model shares an identical reduced form with Romer's horizontal innovation model for some variants. Each model reaches an equilibrium in which the rate of innovation is constant. While equilibria bring analytical tractability, the notion of steady state rates in innovative progress is intuitively unappealing. Indeed, work by Stein (1997) suggests that innovations tend to come in waves (Teitelbaum and Dowlatabadi, 2000).

3. Research Topic

The model in this paper addresses the issues raised in the literature review. Firms are endowed with innovation strategies and they stick to their strategies all their lives. They compete on price and quality of their products and they engage in innovation activities to increase their quality. This continuous stream of product innovations shifts consumers' preferences towards higher quality products. Firms reaching higher quality levels on the quality ladder earlier than their competitors gain a competitive edge in the market. Buyers are heterogeneous and markets are segmented.

This model will enable us to analyse the interaction between R&D activities of firms and heterogeneous consumer preferences in structuring the evolution of an industry. In order to stay competitive, firms introduce ever increasing quality of products to the market either by innovation or imitation. Consumers with heterogeneous preferences act to maximize their utility with their product choices shifting their preferences towards higher quality goods. The model will show how firms and consumers interact in the market environment and how this interaction leads to technological progress. We will also explore whether heterogeneity in innovation strategies is sustainable in the long-term as observed in real life examples and what happens to the market shares of firms having different innovation strategies when a structural market characteristic (market size) or a behavioural rule (R&D intensity) is changed.

4. The Model

This is an agent-based model, agents being firms and consumers. The agents follow pre-specified heuristics (e.g. innovation routines, marketing expenses, product purchases) and react to competitors and environmental conditions (e.g. pricing) and the interactions between these agents at the micro level determine macro outcomes. The model will show how these outcomes are conditioned by the parameters of interest.

Firms pick a price for their goods and put them on the market for consumers' purchase. To make their products visible to potential buyers they make some marketing expenses. Consumers sample a few products and compare them with their previous experiences to buy one that fits best with their preferences. A part of the revenue raised with product sales finances firms' R&D activities. In accordance with their strategy, firms engage in R&D activities and if they succeed, new products are added to their portfolio. Depending upon their competitive performances goods and incumbent firms leave the market leaving their places to new generation of goods and newcomer firms.

4.1. Technology Space

Each product and technology (knowledge) embodied by this product is labelled by an integer number. The words "product", "quality" and "technology" will be used interchangeably in the following. A bigger number corresponds to a higher quality product and a better technology. The units digit of this number shows the version of the product while the rest of the number shows the class the product belongs to. As an example, the number 23 refers to the third version of the second class of products. Hence, each class consists of ten versions. A class is significantly different from any other in terms of its technological level whereas there are only incremental differences between versions in this regard. Products high on the quality ladder (Grossman and Helpman, 1991a; 1991b) -products belonging to higher classes or higher versions within a given class- are intrinsically better than the lower ones. The distance between the highest version in a given class and lowest version in a consecutive higher class is a parameter of the model and there are no defined products in between. Hence the technology space resembles an infinite series of quality ladders on top of each other, each ladder stands for a technology class and each step for a version, and a move from one class to the next requires a jump between the ladders which is only possible with a radical innovation.

4.2. Demand and Supply Structure

Firms compete on quality and price of their differentiated products in an oligopolistic market. There are no production quantity constraints on the firms and all demand is satisfied in every period; there is no stock accumulation or unsatisfied demand. The production cost of a product is linearly related with its quality. Price is initialized as a mark-up over cost and this is the minimum price allowed, which means that sales of a product always bring positive profits and *ceteris paribus* higher quality products mean higher profits. Pricing strategy is a dynamic mark-up heuristic through which firms decide price of each good every period as a function of quality of and profits from that product. Specifically, the proportional change in price is a linear function of the proportional change in the profits on that product in the last two periods. The responsiveness of price to a change in profit is smoothed by a parameter s. A product with no sales in the last but one period is priced at its initial price.

$$C(n) = mq(n) \tag{4.1}$$

$$p_i(n) = (1+\mu)C(n) \tag{4.2}$$

$$p(n,t+1) = p(t) + s(p(t)((\pi(n,t) - \pi(n,t-1)) / \pi(n,t-1))) \tag{4.3}$$

where $C(n)$: cost of product n

m: cost multiplier

$q(n)$: quality of product n

$p(n)$: initial price of product n

μ: mark-up rate

$p(n,t)$: price of product n at time t

s: smoothing parameter

$\pi(n,t)$: profit on product n at time t

If a product's average market share over a specific number of periods is below a threshold level, it is deleted from the market. A firm with no products to sell goes bankrupt. Every period a constant number of firms enter the market, each as an exact copy of an already existing firm, except for its innovation strategy that is randomly determined. The firms that are copied by the new entrants are selected among the firms below a certain market share. This seems a reasonable approximation of reality because in practice most firms start small (de Wit, 2005; Dunne, Roberts, and Samuelson, 1988).

Consumers have what we call a *memory set* which consists of a number of goods selected among all the products the consumer considered to buy in the previous periods. This selection is based on the utility level the product would bring to the consumer in case of a purchase. At every period, the consumer checks whether the products in the memory set are still provided by the market. If any of them is removed from the market, it is replaced by a new randomly selected product. Again at every period, consumers randomly sample a number of products from randomly selected firms. The probability that a product is selected is proportional to the marketing expenses by the firm on that product.

A constant share of the last period's revenue, which is equal for each firm, is spent on marketing activities to make goods visible to the consumers and this marketing budget is shared among products according to their quality level. Specifically, the visibility of a good is the average of the marketing expenses on that good for the last five periods. Price is initialized as a mark-up over cost, which is a linear function of quality, and this is the minimum price allowed. Hence higher quality products bring higher profits and this is why goods consume a share of marketing budget in proportion to their quality.

The newly selected product is compared with the current minimum utility promising product in the memory set and replaces this if it corresponds to a higher utility level for the consumer. Out of this dynamically structured memory set, the good that brings the highest utility is chosen to buy in every period. There are no income constraints faced by the consumers. This product selection heuristic is a decent representation of the basic evolutionary processes of reproduction-keeping the highest utility promising products from the previous periods-, selection-choosing among products to maximize utility-, and variation-a continuous and random selection of new products-. The existence of a memory set and the peculiar way products become visible to the consumers enable us to model brand loyalty and advertising effects, respectively (Malerba *et al.*, 1999).

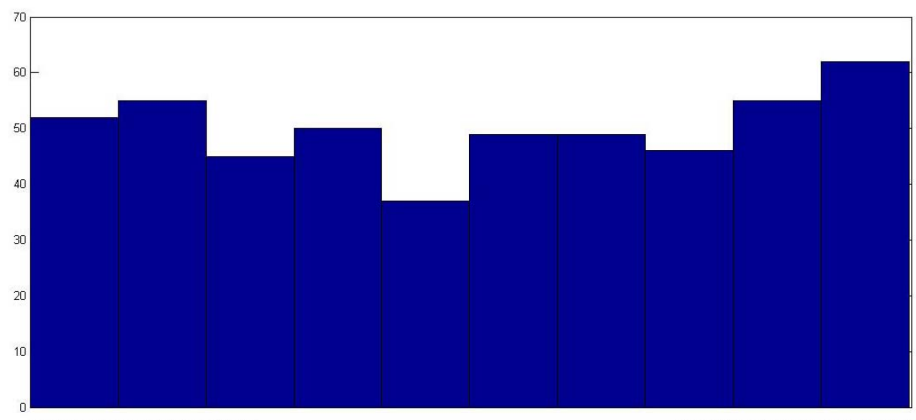

Figure 1. A histogram showing the uniform distribution of the customers' ideal product profiles within the available technology space

Utility is a positive function of the quality and a negative function of the price, and the distance between product's profile and idiosyncratic ideal good specific to each customer profile (Marengo & Valente, 2010). At the outset, the consumers position themselves within the available technology space into consumer profiles or let us say, submarkets. The number of submarkets is constant and each submarket corresponds to a point in the technology space between current minimum and maximum quality levels. The total number of consumers is uniformly distributed into these submarkets and this relative positioning somewhere between the minimum and maximum available technology level in the market is constant through the simulation run. Figure 1 exemplifies this distribution. This formulation allows one to model heterogeneity in consumer preferences; consumers consist of early adopters with a strong preference for high-tech goods, low-price lovers who are content with low quality goods and the ones seeking a balance between price and quality. As technology develops, the level of minimum and maximum available technology improves, preferences shift towards higher quality products increasing the quality of the ideal type good for each consumer. The fact that homogeneous consumers are populating submarkets can be interpreted either as there are as many consumers as the number of submarkets and each of these consumers is making a group buying every period or the submarkets consist of a number of homogenous consumers buying the very same product.

$$U(n,k,t) = [r\{q(n) - \mathrm{mod}(q(n),10)\} + \mathrm{mod}(q(n),10)] - p(n,t) - |(q(n) - q_i(k,t)| \tag{4.4}$$

$$q_i(k,t) = q_{\min}(t) + u(k)(q_{\max}(t) - q_{\max}(t)) \tag{4.5}$$

where $U(n,k,t)$: utility of good n for customer k at time t

r :radical innovation constant

$\mathrm{mod}(q(n),10)$: $q(n)$ mod 10

$q_i(k,t)$: ideal good profile for consumer k at time t

$q_{\min}(t)$: minimum quality level at time t

$q_{\max}(t)$:maximum quality level at time t

$u(k)$: a random pick from a uniform distribution between 0 and 1 for each customer at the outset

The first part of the utility function in the square brackets gives the positive utility derived from the quality of the product. This part is separated into two dimensions: the class that the product belongs to, as given by the part in the curly brackets, and the version of the product within that class which is represented by the unit digit of the product quality number. This separation between class and version of a product in utility terms requires us to use modular operation. Modular operation finds the remainder of division of one number by another. To give an example, A mod B can be thought of as the remainder, on division of A by B. The divisor (B in our example) in our case is 10, because there are exactly 10 versions within each class. A distinction is made between the class and version of a product since consumers attach different levels of values to these dimensions.

Consumers care more about the class of a product rather than its version within a given class. This distinction is operationalized by the parameter r. The parameter r is defined as the radical innovation constant and determines, ceteris paribus, by how much two consecutive versions in different classes differ from each other compared to two consecutive versions in the same class in utility terms. To put it another way, r indicates by how much the first version in a class is evaluated better than the last version in a lower class in comparison to one version is evaluated higher than a one degree lower version in the same class holding all else constant. The higher r the higher is the possibility that higher class products will be preferred over lower class products. $r = 1$ presents a special case where there is no more a distinction between the class and the version of a product. Under such a circumstance it will take longer for the inferior products to be eliminated, product range will increase and technological change and hence wealth creation will slow down, since consumers no more put a premium on radical innovations.

The price of a product appears in the utility function with a negative term. The last part of the utility function in the absolute terms gives the negative utility due to consuming a non-ideal product. This form of the utility function allows one to model heterogeneity in consumer tastes with the inclusion of the distance of the candidate product from the ideal one and to model the process whereby products transform from non-invented to invented and from cutting-edge to obsolete in time with a continuous shift of preferences towards higher quality products as explained in the preceding paragraph. This process is especially accelerated with an r value higher than 1.

4.3. Innovation Function and Strategies

Innovation is defined as the emergence of a new product. The firm chooses a product to invest in from its portfolio and does R&D. The quality level of this product also shows the knowledge base of the firm in that specific project. Innovation size is modelled as a random pick from a Poisson distribution with an arrival rate which is a function of the quality of the product invested in and the R&D budget devoted to that project (Minniti *et al.*, 2008). The arrival rate is a negative function of the quality of the product to invest in: complexity of the product decreases the likelihood of the research success. And there are diminishing returns to R&D; additional investments increase the arrival rate in a decreasing manner. Hence, a lower level for the complexity of the knowledge base and more R&D investment increases the size of an innovation. A constant share of the last period's revenue is allocated to R&D every period and this share does not differ among firms.

When innovation occurs, the resulting difference (the size of the innovation) is added to the chosen product's technology level. A new product embodying a new technology and a higher technology base emerges. If the newly innovated product is in a higher class, then we have a radical innovation. Otherwise we have an incremental innovation. Depending on the radical innovation constant (r) parameter value, radical innovations may render old technologies in the market obsolete whereas incremental ones do not have such an impact. Hence a radical innovation may disturb the profit stream from the lower-class products which means that a firm can cannibalize its own products. This feature is introduced to the model with the specification of the utility function whereby higher-class products will have a market stealing effect on the lower-class products.

In the case of a radical innovation, the size of the innovative step is large enough to cover the sum of the distances between the knowledge base and cutting edge technology in the respective class and the distance between two consecutive classes where no products are defined. The size of an innovative step is limited to a maximum of one radical innovation at a time. When there is a radical innovation, the newly innovated product will be allowed at most to be the lowest version in the new class and nothing higher. This constraint negates the possibility that knowledge base achieved in the previous class helps explore the technology space of the new class of products. If the resulting innovation appears to be in the interval between two classes where no products are defined, then the innovation project is assumed to fail.

$$\lambda(n,i,t) = \frac{R(n,i,t)^{\alpha}}{q(n)} \tag{4.6}$$

$$\delta(n,i,t) \sim Pois(\lambda) \tag{4.7}$$

$$q(n') = q(n) + \delta \tag{4.8}$$

where $\lambda(n,i,t)$: innovation arrival rate for product n of firm i at time t

$R(n,i,t)$: R&D investment of firm i in product n at time t

$q(n)$: quality level of product n

α: innovation productivity parameter

δ: innovation size, a random pick from a Poisson distribution with arrival rate λ

$q(n')$: quality level of the innovated product

Imitation is defined as creating an exact copy of another firm's product. Once the product to invest in is chosen within a firm's own portfolio, the firm determines the expected size of the imitative step given its R&D budget and base technology. Then, it searches through the product sets of other firms to find this prospective target product. If this product is not innovated yet or not extant anymore, or if the number of imitative projects is higher than one, the firm seeks for a one step lower product and continues this search until the number of target products found is equal to the number of imitative projects. If needs be, the firm repeats this search cycle with the next base product. After this search process is over, if the number of target products falls short of the number of imitation projects the firm plans to carry out, idle R&D budget is transferred to the marketing budget for the next period. The size of the imitative step is modelled with the same function given for innovation projects except for the fact that R&D investment is more productive in imitation than in innovation. If imitation succeeds, –the imitative step is at least as large as the distance between the base product and the target product- the end result of the project can only be the target product itself and nothing else. Even if the imitative step is bigger than the difference in the technology levels, the firm will be assumed to achieve the target quality, but no higher.

$$\lambda(n,i,t) = \frac{R(n,i,t)^{\beta}}{q(n)} \quad (4.9)$$

$$\delta(n,i,t) \sim Pois(\lambda) \quad (4.10)$$

$$q(n') = q(n) + \delta \quad (4.11)$$

where $\lambda(n,i,t)$: imitation arrival rate for product n of firm i at time t

$R(n,i,t)$: R&D investment of firm i in product n at time t

$q(n)$: quality level of product n

β : imitation productivity parameter

δ : imitation size, a random pick from a Poisson distribution with arrival rate λ

$q(n')$: quality level of the imitated product

In picking R&D projects, firms pursue either a technology-push or a demand-pull strategy. Technology-push firms select R&D projects starting from the highest technology base they possess to come up with cutting edge technology possible for them (technology-driven). Demand-pull firms start from the technologies with the highest market share with the hope of attaining products which will maximize their profits in the following periods (market-driven). The number of R&D projects a firm plans to realize in every period is a parameter of the model and this value is higher for "diversified" firms in comparison to that of "focused" firms. If a firm engages in more than one project at a time, R&D budget is equally distributed among the projects.

Hence, the firms are bound to follow one of the eight strategies throughout the simulation run: diversified demand-pull imitation, focused demand-pull imitation, diversified technology-push imitation, focused technology-push imitation, diversified demand-pull innovation, focused demand-pull innovation, diversified technology-push innovation and focused technology-push innovation. The financial resources required to imitate a product are lower than to innovate one and the chance of success is higher. However, the profits especially from a new-to-the-market innovation are higher compared to an imitated product for which the market is already satisfied at least to some degree. In the case of demand-pull projects, as market conditions guide the decisions, there is a higher prospect for new products bringing about above-average profits with a small variance. However, for technology-push R&D, despite prospects of profitability are more uncertain, the likelihood of ending in top-notch or new to the market products is stronger compared to market-driven ones. As for the difference between a focused vs. diversified strategy ("breadth" of the innovation strategy, Marengo *et al.*, (2009)), some firms prefer spreading their R&D budget over a range of products whereas others go for focusing on one product. A wider scope of search may help distributing the risk and bring about better prospects for profits in different market niches (classes of goods). However, the size of the innovative and imitative step will decrease in the number of projects as total R&D budget will be shared among a larger set of products.

4.4. The Pseudo-Code of the Model

At the initialization period market is populated with N firms with a random product portfolio and each consumer is assigned to a submarket. The routine for the rest of the simulation is implemented as follows:

1. Firms set a price for their each product as a function of profits from that product in the previous periods
2. Firms make marketing expenses for their each product as a function of the quality
3. Each consumer determines her ideal product
4. Consumers structure their memory sets and purchase the best product within this set
5. Products with an average market share below a threshold level are deleted from the market. Firms with no products to sell leave the market. New firms enter
6. Firms do R&D in accordance with their innovation strategies and new products are added to firms' portfolio

5. Simulation Results

5.1. Model Dynamics

In the following we will present the results of the simulation analysis[2]. The data for the analysis is produced as an average over 100 simulation runs of 1000 steps using the base model configuration. The only thing that changes from one simulation to the other is the seed value which is a number used to initialize the pseudorandom generation process. This seed value governs all the stochastic processes within the model and two simulations with the same seed value always give the very same results. We start with introducing the evolution of the main variables of interest in the model to answer our two research questions: whether heterogeneity in innovation strategies is sustainable in the long run and how R&D activities of firms and heterogeneous consumer preferences interact in structuring the evolution of an industry.

Figure 2 traces the time-path of the market shares of the groups of firms following one of eight different strategies. The figure shows that heterogeneity in firms' innovation strategies is sustainable; every strategy enjoys a positive market share throughout the simulation run. Figure 2 also signifies a shake-out of the market shares in the initial periods followed by a dispersion and stabilization for the following terms.

[2]The model was implemented on the Laboratory for Simulation Development platform (Valente, 2008). Software and documentation for the platform are available at www.labsimdev.org. The code and configuration file of the model is available from the author upon request

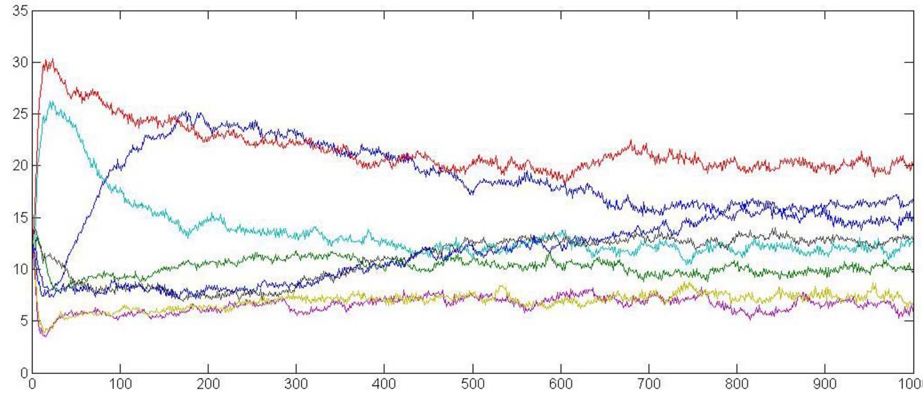

Figure 2. Market shares (%) of firm groups following different innovation strategies through time

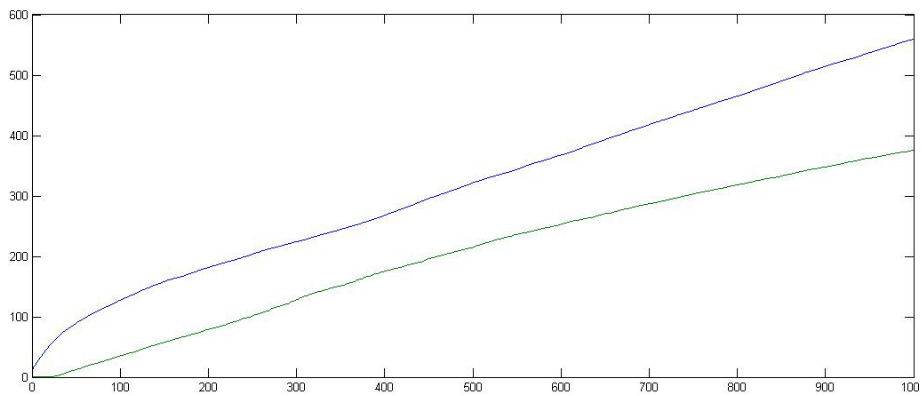

Figure 3. Maximum (upper series) and minimum (lower series) quality levels available through time

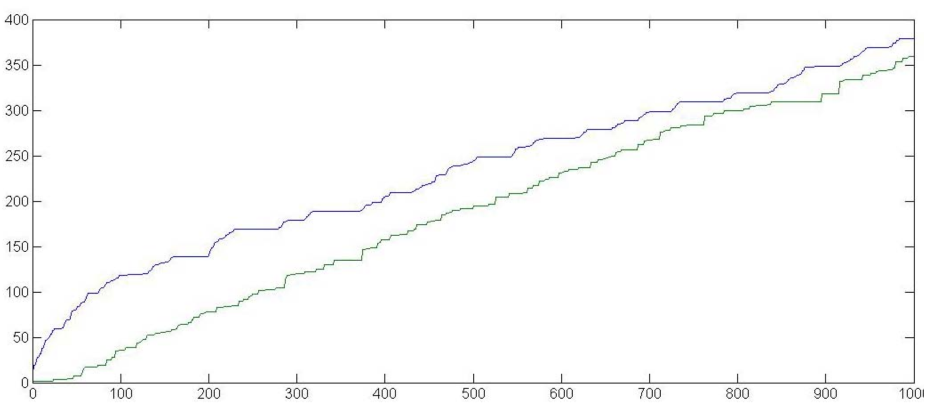

Figure 4. Maximum (upper series) and minimum (lower series) quality levels available for a single run through time

Figure 3 allows us to observe the maximum (upper series) and the minimum (lower series) level of qualities available in the market. Whereas the maximum quality level is mainly determined by the R&D activities of the firms and the minimum level mainly by the competitive forces and heterogeneous consumer tastes, the interaction between demand and supply dynamics affects these levels both. The continuous introduction of new products by innovation raises the maximum quality and renders low quality products obsolete by shifting consumer preferences towards high-tech products. Technological change is the engine of economic growth in this model. If for some reason technology creation comes to a halt (e.g. imitators conquer innovators dominating the whole market and leaving innovators with no financial resources to innovate), wealth creation also stagnates. Therefore both consumers and imitator firms depend upon innovators firms to prosper. Drawing upon this graph, the reader should not be deceived that the model produces innovative progress at a steady state growth rate. It should be reminded that the above graph is created using data as an average over 100 simulation runs. When we observe the same series for a single as in Figure 4 above, we see that innovations come in waves; times of rapid technological change is followed by stable periods when there is no technological advancement at the sector level.

5.2. Simulation Experiments

This subsection includes the results of a series of simple experiments designed to help us explain our next research question; what happens to the market shares of firms having different innovation strategies when a structural market characteristic-market size-or behavioural rule-R&D intensity- is changed is. The analysis in this section is based on data derived as averages of end of simulation values of variables over 100 simulation runs each with a different seed value. At this point the reader should be reminded that there are three strategy pairs which make a total of eight exclusive strategies: innovation vs. imitation, technology-push vs. demand-pull, and focused vs. diversified.

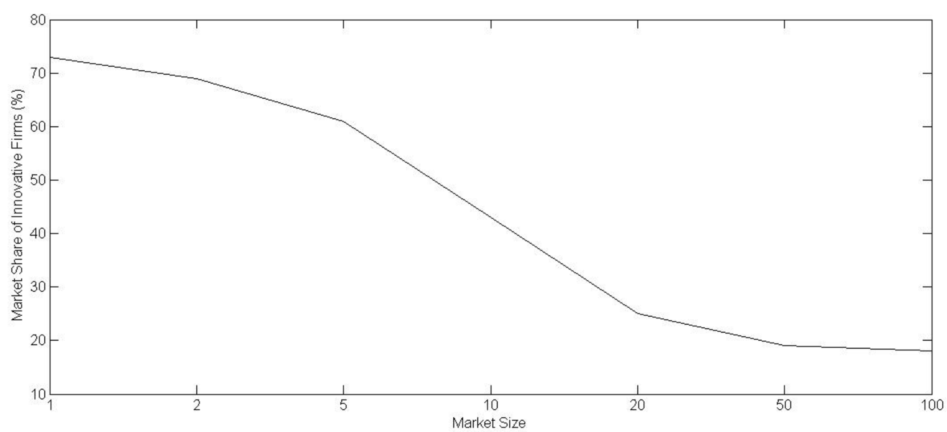

Figure 5. The market share of innovative firms as a function of market size

The first of our graphs is to explore the relationship between market size and market share of innovative firms. Figure 5 depicts that a bigger market size is more conductive to the imitative firms than it is to innovative ones. Within this model, market size refers to the total number of consumers populating each homogenous submarket. The explanation for this downward sloping line lies in the fact that R&D investments are more productive in imitation than in innovation. A bigger market with many consumers means higher revenues and hence higher budgets allocated to R&D. Working with these higher R&D budgets emphasizes the productivity differential between imitators and innovators. It is easier to imitate a product than to innovate one with a given R&D budget. We can conclude that a higher number of consumers means a higher change of living for imitators.

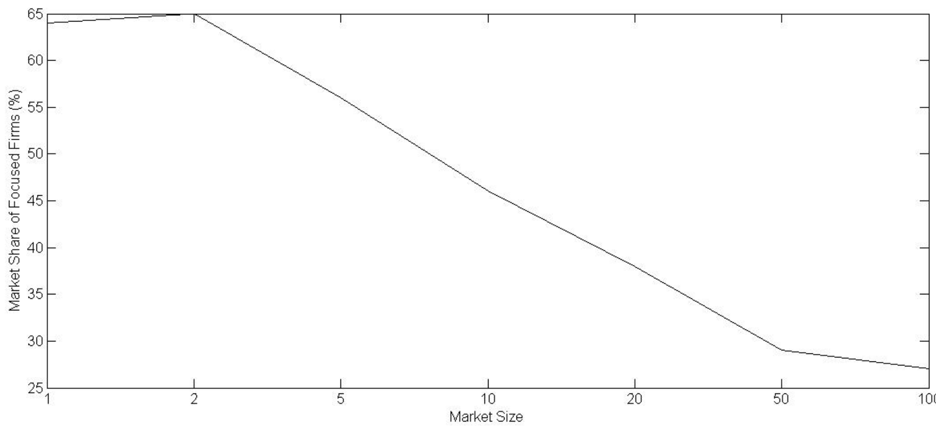

Figure 6. The market share of focused firms as a function of market size

Figure 6 shows that focused firms lose their market share to diversified firms as market size increases. Focused firms conduct a single R&D project at a time whereas diversified firms share their R&D budget equally among a few projects. Multi-project firms have a better chance to have a richer product portfolio which enables them to service several submarkets simultaneously; hence they can control a larger share of the market. But the drawback to this strategy is that this is only possible if R&D budgets are high enough to finance these projects. Because, the size of the innovative and imitative step will decrease and the possibility of failure in these projects will increase in the number of projects as total R&D budget will be shared among a larger set of products. A limited R&D budget means a slower technological progress for diversified firms in comparison to focused ones if no technological progress at all. This trade-off explains the general downward trend in Figure 6. An increase in markets size gives a boost to R&D budgets which gives and edge to diversified firms over the focused ones.

Our next graph is to see the effect of market size on market sharing between technology-push and demand-pull firms. Demand-pull firms, guided by market conditions, search the technology space within the vicinity of their products with the highest market share while technology-push firms aim at fastest technological progress possible. Especially in the short term technology-push firms investing in the most developed technologies they have lose their market share to demand-pull firms investing in the products most preferred by the consumers. When market size is larger, it is more rewarding to behave according to the signals from the market. That is why demand-pull firms increase their market share as market size enlarges as seen in Figure 7.

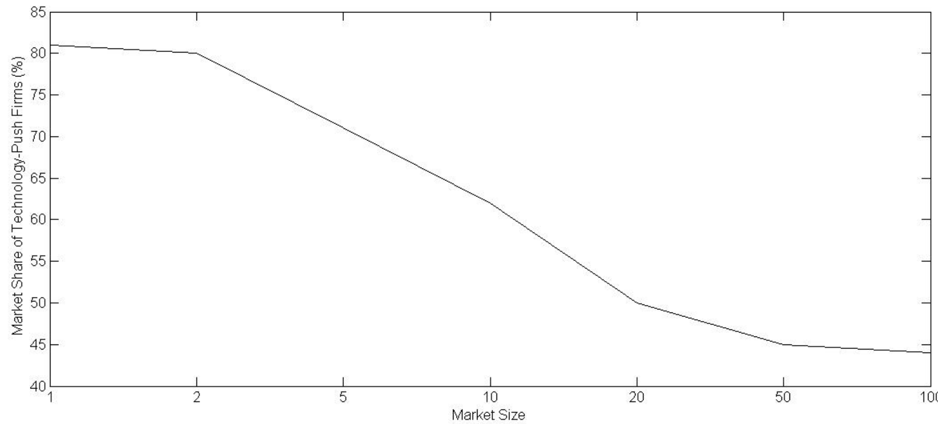

Figure 7. The market share of technology-push firms as a function of market size

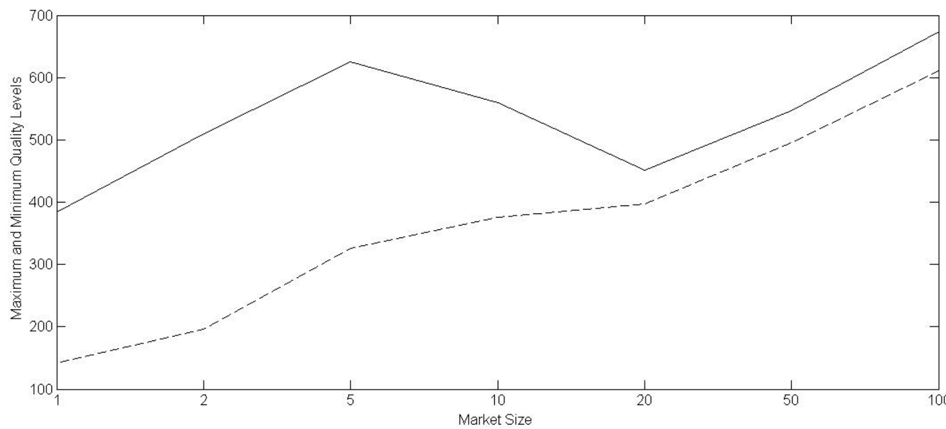

Figure 8. The maximum (upper series) and minimum technology levels (lower series) as a function of market size

Figure 8 reports maximum and minimum technology levels as a function of market size. As market enlarges, there is an initial increase in the level of maximum technology interrupted by a local peak and then it starts to decrease. After a local minimum, further enlargement of the market results in higher levels of maximum technology. One expects the maximum level to rise monotonically; a larger market means higher revenues which in turn mean higher R&D budgets. Additional financial resources for innovation accelerate technological change and minimum technology level keeps pace with maximum technology level. However, there is more to this explanation than what is covered above. Innovator firms mainly determine the pace of technological change and a larger market decreases the market share of innovators as explained in Figure 5, depriving them of highly needed R&D investments to achieve the highest technology level possible. This explains why for the middle ranges of the market size a decrease rather than an increase is observed in the maximum technology level. Hence, the negative relationship between the market share of innovators and market size is the reason why the initial expectation does not come true. Beyond a critical value, even further increases in the market size equip innovators with adequate R&D budgets to speed up technological development even if that increase brings about market share shrinkages on the part of innovators.

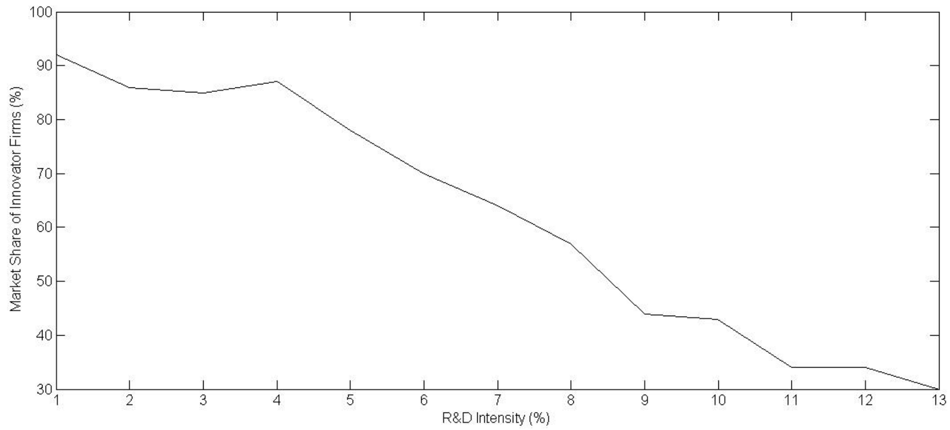

Figure 9. The market share of innovative firms as a function of R&D intensity

From this point onwards the analysis continues with the effects of R&D intensity on market sharing between different strategies. Figure 9 shows the market share of innovative firms as a function of R&D intensity. The figure depicts that a higher R&D intensity decreases the market share of innovative firms. The explanation for this is parallel to the explanation of Figure 5. Imitator firms are more productive than innovators in doing R&D. A higher R&D intensity means a larger part of the revenue income is devoted to R&D and this financial resource is more effectively used by the imitators.

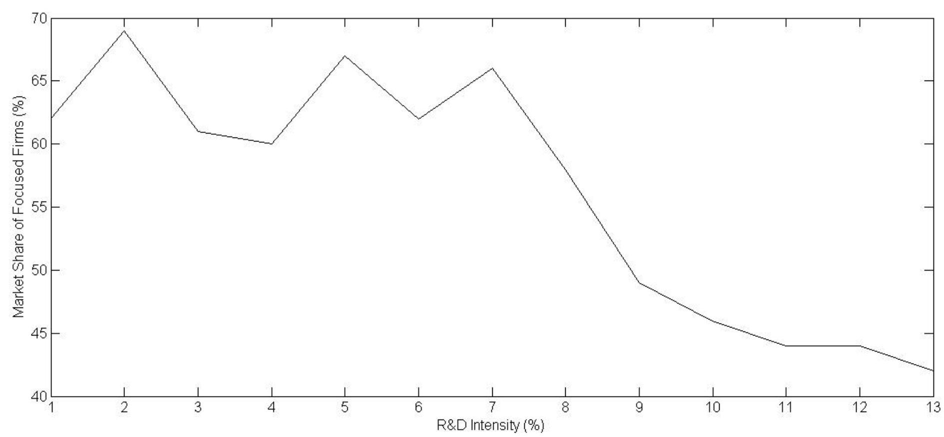

Figure 10. The market share of focused firms as a function of R&D intensity

In Figure 10, we observe how the market share of focused firms decreases with an increase in R&D intensity. As one would remember, focused firms conduct a single R&D project at a time whereas diversified firms share their R&D budget equally among a few projects. Multi-project firms' advantage is the higher chance of achieving a more diversified product portfolio which helps them satisfy heterogeneous consumer submarkets simultaneously whereas focused firms' advantage lies in a higher chance of success in R&D projects and a higher size of an imitative or innovative step-faster technological progress- since they invest their R&D budget in only one project at a time. Whether imitators or innovators exploit their strategic advantages more effectively is determined by the level of R&D resources. When R&D intensity is low, diversified firms do not possess the required financial resources to succeed in more than one project conducted at the same time. A high R&D intensity equips them with the highly needed finance to achieve a diversified product portfolio.

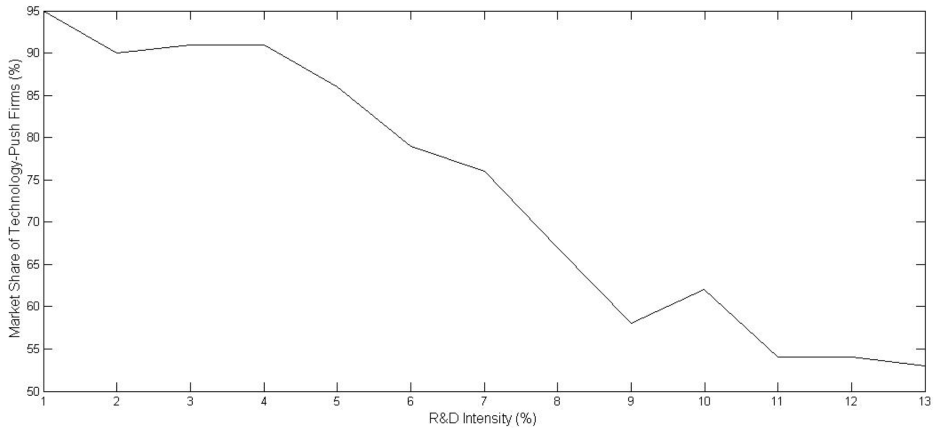

Figure 11. The market share of technology-push firms as a function of R&D intensity

Our next graph is to see the effect of R&D intensity on market sharing between technology-push and demand-pull firms. Demand-pull firms invest in the technologies with the highest market share whereas technology-push firms invest in the most improved technologies they possess. Therefore, we can argue that demand-pull firms aim at short-tem profit maximization and technology-push firms go for the fastest technological progress. This difference in the followed strategies favour technology-push firms in the long-run as consumers shift their preferences towards the highest quality goods, and hence towards technology-push firms owning these technologies. Being technology leaders brings with it being market leaders in the long-run. But this is only possible if the R&D resources are binding, because the maximum innovative or imitative step is limited by one radical innovation at a time. When R&D intensity is low, technology-push firms pace technological change as they always invest in the most improved technology they have and this gives them advantage over the demand-pull ones. However, when R&D intensity is high and hence financial resources are abundant, R&D budgets are no more binding and independent of their base technology choices in their R&D projects, demand-pull firms can keep up with the pace of technological change which is limited in this case with one radical innovation at a time. The inverse relationship between the market share of technology-push firms and R&D intensity in Figure 11 confirms this explanation.

Figure 12 reports maximum and minimum technology levels as a function of R&D intensity. An immediate expectation is having consistently positively sloped lines; a higher R&D intensity means higher R&D budgets which lead to faster technological progress. But as seen in the figure this is not the case after the middle ranges of the R&D intensity value. The reason for the maximum technology level to peak at a middle range of the R&D intensity and to level off thereafter should be looked for within Figure 9. A higher R&D intensity causes innovators to lose their market share to imitators diminishing their revenues. Working with a higher R&D intensity does not compensate for the loss in revenues and hence cannot accelerate technological progress continuously.

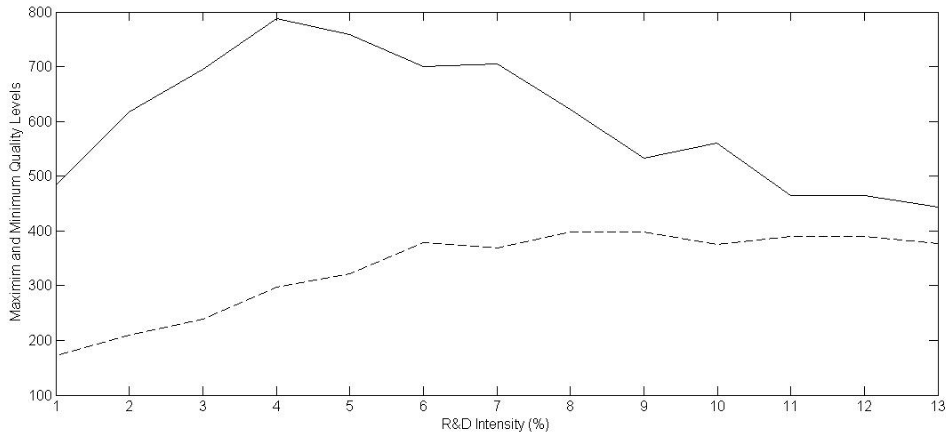

Figure 12. The maximum (upper series) and minimum technology levels (lower series) as a function of R&D intensity

6. Conclusion

This paper is meant to analyse the interaction between R&D activities of firms and heterogeneous consumer preferences in structuring the evolution of an industry and heterogeneity in firms' innovation strategies. The question whether heterogeneity in firms' innovation modes is sustainable in the long run and how market sharing between firms following different strategies is determined by a structural and a behavioural parameter of the model is examined. The proposed methodology is to develop an evolutionary, multi-agent based, sector-level innovation model addressing the supply and demand side of the market simultaneously with the co-evolution of heterogeneous consumer preferences, heterogeneous firm knowledge bases and technology levels at the micro level. The main discretionary activities of the firms are product innovation and imitation together with pricing of these products. The consumers, under computational constraints, aim at maximizing their utility with product choices. The competitive market provides these actors the required medium for interaction. A simultaneous consideration of technological progress and market dynamics with the help of agent-based modelling techniques allowed us to analyse such a multi-faceted phenomenon of heterogeneity in firm innovation strategy.

The model concludes that co-existence of a variety firms with distinct innovation strategies is viable even in the long run. There are exactly three strategy pairs which makes a total of eight distinct strategies: innovators vs. imitators, technology-push vs. demand-pull firms and focused vs. diversified firms. Innovators can live together with imitators, the existence of technology-push and demand-pull firms is not mutually exclusive and one can observe focused and diversified firms simultaneously within the same industry. This outcome is consistent with the empirical findings referred to in literature review; selection process does not pose homogeneous behaviour in innovation modes. This heterogeneity emerges as a dynamic equilibrium with continuous technological change and firm entry/exit.

The model results also show that the fate of firms with distinct strategies is determined both by market size and R&D intensity. A larger market favours imitators against innovators, demand-pull firms against technology-push ones and diversified firms against focused firms. In a similar vein, adopting a higher R&D intensity at the industry level increases the market shares of imitator, demand-pull and diversified firms. The pace of technological progress is affected by this very market sharing between different strategies throughout the simulation run. A larger market or a higher R&D intensity does not directly translate into a faster technological change, since it is also a function of the innovators' market share. If an increase in the size of the market or in R&D intensity cannot compensate for the loss of market share by innovators, one can even observe a slowdown in technological change.

In this paper, firms are endowed with an innovation strategy and they do not change it throughout the simulation. A radical extension to this study will be the endogenization of the innovation strategies by letting firms freely choose and possibly change their strategies in time due to varying market and technological conditions rather than an exogenous imposition of strategies right from the beginning. Firms can even adopt different strategies simultaneously in different product development projects. Such a formulation would be a much more realistic representation of firms and let us study firm specific and aggregate factors leading to adoption of and shift from/to different strategies.

Appendix

1. Initialization of the main parameters of the model

FirmNum=200: the initial number of firms
SubmarketNum=500: the number of submarkets
marketsize=100000: the number of consumers
MinTech=1: the minimum initial technology level
MaxTech=10: the maximum initial technology level
betainn=0.5: the productivity of innovation
betaimit=0.65: the productivity of imitation
ris=3: the size of the gap between two consecutive goods in different classes where no products are defined
pricespeed=0.1: the speed with which price of a product respond to change in its profits
pm=30 per cent: profit margin
cm=1: the parameter that links the initial price of a product to its quality
MaxNumProd=5: the minimum initial number of products
MinNumProd=10: the maximum initial number of products
marketingshare=10 per cent: the share of marketing expenses in total revenue
r&dintensity=10 per cent: the share of R&D budget in total revenue
ric=2: radical innovation constant in utility function
techidealconst~Uniform(0,1): the parameter picked from a uniform distribution that defines the ideal product for a consumer between minimum and maximum technology level available
MemorySize=5: the number of goods in the memory of a consumer
GoodNum=5: the number of new goods consumers evaluate for a purchase every period.

2. Main variables of the model

TechMax: the maximum technology level
TechMin: the miniumum technology level
Ms_Inn: market share of the innovators
Marketing: marketing expenses of a firm
R&DBudget: R&D budget of a firm out of its total revenue
Price: price of a product
Profit: profit from a product
TechIdeal: the ideal product for a consumer between minimum and maximum technology level available
Utility: the utility level derived from a good by a consumer

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